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LARA: NEAR TERM RECONFIGURABLE CONCEPTS AND COMPONENTS FOR LUNAR EXPLORATION AND EXPLOITATION

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ABSTRACT

NASA's Exploration Initiative requires tools to support of near term human activities on the Moon or Mars. ANTS Architecture is well suited to such applications using current ElectroMechanical Systems (EMS) for Addressable Reconfigurable Technology (ART). We have analyzed the nature and behaviors required of ANTS components for such an application designated LARA (Lander Amorphous Rover Antenna). Basic structures are highly modular, addressable arrays of robust nodes, from which highly reconfigurable struts, tethers, and fabric are autonomously and reversibly deployed for all functions. An ANTS craft is an appendageless multi-tetrahedral structure, harnessing the effective skeletal/ muscular system of the frame itself to enable more 'natural' movement, effectively allowing 'flow' across a surface or into a particular morphological form. Individual craft would be deployed, with or without a human crew, land, using a miniaturized version of high impulse thruster technology, transform into rovers, bowl-shaped antennas, hut-like human shelters, or more specialized service providers, as needed, and ultimately return to the point of deployment. We have developed conceptual and physical models of ANTS systems to determine design requirements and are currently working on an EMS-based prototype. ANTS structures could be thus used for exploration, reconnaissance, communication, transportation, and construction, , protecting human crews and facilitating their work.

CONTEXT OF THE ANTS APPROACH

The ANTS approach to exploration [1,2,3,4,5] discussed here is directly relevant to the NASA's Exploration Initiative goals of sustainable and affordable robotic exploration of the solar system [6,7]. The mission application, Lander Amorphous Rover Antenna (LARA), is particularly in line with the new Initiative goals for the Moon and Mars, where the focus is on establishing human crews with robotic assistance in bases on the Moon and Mars and exploring to search for evidence of resources, biological precursors, or life itself [6,7].

The LARA concept would result in further development of enabling technologies identified in the Initiative [6,7] as well: a) sustainable autonomous systems and robotics, b) advanced, reusable, transportation in space and on the ground, and c) reliable, durable, modular systems and structures.

In this paper, we will describe the conceptual framework, design, and models, for LARA, based on ongoing work. We will identify requirements and essential features, and assess capabilities the ANTS architecture to provide reconnaissance, transportation (lander and rover), communication, and shelter, and other functions to support the establishment of a human presence on the Moon and Mars (**Tables 1 and 2**).

What is the nature of the contribution to exploration of the Moon and Mars that the ANTS architecture can provide through the use of the LARA concept [8a,8b] **(Tables 3 and 4**)? The LARA concept could be implemented within the next decade using current technology, and be available to assist the human return to the Moon in 2015-2020, to prepare for human exploration of Mars. By using the structures themselves as a skeletal muscular frameworks, LARA craft use a dramatically new strategy of transforming themselves for the required activity enroute to or on the surface, providing far higher flexibility for visits to multiple targets and cost effectiveness than the currently utilized approaches, where the major systems, landing, surface transportation, and communication, require separate structures. Stowed LARA craft could be launched from Crew Exploration Vehicles. Reconfigurable, reshapable LARA craft could also be used to provide temporary shelters or to enclose natural formations, such as lava tubes, providing permanent shelters, as tools to search for and acquire natural resources, or, collectively, as antenna arrays for communication on the ground or in space.

On the Moon, starting in about a decade, the use of the LARA concept would

Table 1: Lunar Mission Strategy for the Exploration Initiative relevant to LARA

- Lunar Exploration activities as 'testbed' enabling sustained human and robotic exploration of Mars and more remote targets
- Series of robotic missions begin in 2008 to prepare for later human exploration of lunar surface
- First extended human exploration missions begin in 2015-2020 time frame
- Lunar exploration missions make scientific discoveries, develop new technologies and approaches, identify resources to support sustained activity in space.

Table 2: Mars Exploration Initiative relevant to LARA

- Robotic exploration goals include searching for evidence of life, understanding solar system formation, and preparing for future human exploration;
- Robotic exploration of other solar system bodies, such as asteroids, continues in parallel.
- Develop key capabilities to support long duration combined human and robotic exploration, including power generation, life support, transportation, communication.
- Human exploration of Mars begin after robotic missions have completed full reconnaissance of the planet and human presence on the Moon becomes sustainable.

Table 3: LARA Solution
• Robust, 'form follows function' craft transform providing all key functions: transportation in space and on the ground, communication, shelter, resource identification and capture. • LARA systems deployable from Earth/Earth orbit, Space Station, or Moon/Lunar orbit and operate autonomously as robotic mission or through interface to support human exploration. • LARA rover capable of operating in terrains with high and variable relief and roughness inaccessible to appendaged vehicles through capability to continuously change scale, motion, and gait with many degrees of freedom.

thus enable the goal of performing a global reconnaissance of resource potential, as roving robotic explorers with or without humans, and of providing a testbed for the human return to Mars. LARA systems would allow the human/robotic interface to be fully optimized with less risk of failure.

On Mars, starting in about two decades, the LARA craft could be used for a robotic mission capable of returning samples from the most desirable locations from the standpoint of the search for life and water: cracks, crevices, and caves. Mars terrain, particularly the volcanic terrain of interest, is highly fractal and thus so extremely hazardous as to be inaccessible to permanently appendaged (wheeled or legged) vehicles.

THE ANTS CONCEPT

ANTS SMART (Super Miniaturized Addressable Reconfigurable Technology) architecture was initiated at Goddard Space Flight Center (GSFC) to develop a revolutionary approach to space vehicles and systems epitomizing the 'form follows function' approach. Such craft are capable changing form to optimize function or to adapt to environmental demands (4,5). The basic unit of the structure is a tetrahedron consisting of nodes interconnected with struts that can be reversibly and/or partially deployed or stowed to allow motion, forward on a surface, at a controllable scale or gait. 3D networks are formed from interconnecting reconfigurable tetrahedra, making structures which are scalable, massively parallel systems. As more tetrahedra are interconnected, the degrees of freedom are increased and motions evolve from simple to complex, and from stepped to continuous. ANTS Addressable Reconfigurable Technology (ART) can be constructed from the available electromechanical systems available. The prototype is being constructed from macroscopic electromechanical systems (EMS)-***ART,*** and LARA could be developed at this level of technology. As Micro-EMS (MEMS ART, Miniaturized ART or ***MART)*** or nano-EMS (Super Miniaturized ART or ***SMART)*** become available, within the next decade or two, such components could be incorporated to minimize mass and power requirements. The 3D network of actuators and structural elements is composed of nodes that are addressable as are pixels in an LCD screen. The full functionality of such a system requires fully autonomous operation, and will ultimately be realized through a neural basis function (NBF) possessing the capability for actuator-level autonomic response and heuristic-level decision-making, which will be discussed elsewhere (9a,9b,9c,9d). The ANTS architecture for LARA will be discussed here.

LARA: APPLICATION OF ANTS TO EXPLORATION OF TERRESTRIAL PLANETARY SURFACES

What have we learned from our attempts to explore the surface of the Moon **(Table 4**)? The campaign for human exploration of the solar system was inaugurated with the Apollo Program. The challenge of launching a human crew along with a large payload to support them into deep space, delivering them into orbit around

Table 4: Moon and Mars Exploration Lessons
We can deliver a human crew to another body, keep them on the surface for at least a short time, and return them safely.
A human crew provides a more effective surface exploration tool than rovers alone.
Exploration with humans is costly.
We can deliver rovers to another body and keep them on the surface indefinitely.
Rovers can move to, collect samples and send back analyses from relatively easy targets selected through human telepresence.
Rovers have limited coverage and limited flexibility for dealing with the range of challenging terrains.
How could we increase cost effectiveness of human crews and effectiveness of rovers?

Table 5: LARA Characteristics
* Support, sustain robotic or human exploration
* Operate autonomously, singly or collectively, with or without human partners
* Key functions include lander, rover, antenna, reconnaissance, shelter
* Surface targets by preselection or opportunity
* Search for resources, evidence for life
* Cover many kilometers/day on ground.
* Operation on any surface
* Propulsion in Space: Mini Chemical Thruster
* Propulsion on Ground: Node and Strut
* Power: solar or nuclear batteries

another body, landing them on that body, returning them alive from another its surface, and having them gather a scientifically useful payload from that surface was a remarkable achievement, one that was accomplished in ten years and then repeated successfully 6 times. As a result of the samples gathered from the surface and data gathered from orbit, major advances were made in our understanding of planetary formation and conditions for the origin of life [10,11].

Although only limited portions of the lunar surface were sampled, the Apollo Program was cancelled early. Some mission operations were automated, but not autonomous, with control resident on the ground, resulting in high demand for resources, time and expense despite the limited duration (days) of the missions. Many questions, which demand the gathering of samples from the still largely unexplored lunar surface, remain unanswered. Clearly, the development of autonomous systems and robotics was required to cut down on the use of resources. But, well trained and curious human explorers are extremely valuable in guiding the discovery process, as witnessed by the extraordinary job done by the astronauts in selecting and documenting the sites they visited. The lesson here apparently is that, in order to make exploration sustainable, additional support required for human activities should be utilized as an important enhancement to truly autonomous robotic exploration, when the human presence is critical for leading the exploration.

What have we learned from our attempts to explore Mars (**Table 4**)? The exploration of Mars, largely driven by interest in the possibility of finding life on Mars, has been entirely remote, and, more recently, robotic. Mariner 9 was the first spacecraft to orbit Mars, but revealed nothing until the global dust storms cleared. Viking orbiters, Mars Global, Surveyor, and Mars Odyssey have revealed progressively more details of Mars complex terrane as instrument resolutions have improved: evidence for the largest mountains (volcanoes) and canyons observed in the solar system, and a past global magnetic field [12]. These missions most striking revelation is that water has played a major role in creating Mars landscape: cyclical climate changes have caused periodic ice ages [13] which have resulted in massive outflow channels, and loss of an earlier ocean [14]. Speculation and now substantial evidence for the existence of liquid water on Mars surface has resulted in renewed interest in the search for life on Mars [15]. Rovers have been deployed to look for this evidence in samples. Viking Landers had indicated Mars was covered with weathered iron-rich clay derived from basalt in a rugged terrain, a result confirmed by Mars Pathfinder [16,17]. Viking biological experiments had given unexpected, but not convincing results, for the presence of life [16]. Mars Exploration Rovers Spirit and Opportunity have collected many samples on their traverses within a small area, and, with the finding of hematite deposits, given even more evidence for the presence of liquid water during formation of these samples, but have not found water in the present [18].

Of course, the limitations of robotic rovers prevent them from going to the more rugged landscapes. Their permanent appendages, wheels in this case or even the 'leg's that are planned, make them relatively inflexible, optimize them permanently for operation over a limited range of landscape scales. But it will be highly fractal landscape, with constantly varying scales of relief and roughness where the deep fissures buried in chaotic outwash channels, where life would continue to exist on Mars. Because the risk of injury to appendages is great even in the typical desert pavement being traversed, extensive decision making must go into every step, placing tremendous demands for autonomy that are difficult to meet. As a result, the cautious, slow (due to the roundtrip light time to Mars) telepresence approach to navigation will continue to be limit autonomy and coverage. The lesson here may be that we need a dramatic breakthrough in our approach to robotic rover design in order to locate and reach areas most likely to contain evidence for life with any degree of autonomy.

The LARA application of ANTS architecture, summarized in **Table 5**, uses application of EMS (ART) level systems which are currently available, or MEMS (MART) level system which will become available over the next two decades, to address the two the greatest challenges in longer duration missions far more effectively than existing vehicle designs. These challenges are a) the need for far greater flexibility and autonomy in robotic operations, and b) the need for far more sustainable and efficient use of expendables for autonomous operation and for crew support and protection.

The ANTS architecture creates a space filling material from addressable, reconfigurable, self-similar components which provides a skeletal muscular framework. The structural components themselves are flexible, allowing adaptation, through their reversible rapid reconfiguration over seconds, for functions required at each phase of a mission. ANTS reconfigurable structure thus reduce mass, power, and expendable requirements by eliminating the need for specialized systems for key functions such as space and ground transportation, communication, and shelter.

We first considered the Autonomous Nano-Technology Swarm (ANTS) architecture for a future application, the PAM concept, which is discussed in detail elsewhere [19,20,21] (See ANTS: The Movie at the official ANTS website [1]).. Here we consider the LARA application in detail **(Figure 1).** (See LARA: The Movie at the official ANTS website [1]). The LARA craft is transformed from lander to rover over rugged terrain, to various functions, all described in **Table 6**. These include antenna for transmitting or receiving information, carrier for a payload such as a sample collector/analyzer, to provider of crew shelter. These functions could be performed autonomously, or through interface with crew either in situ or remote.

Table 6: LARA Forms and Functions

Function	Form
Lander Space Mobility	Flattened with mini- thrusters at edges
Amorphous Rover Surface Mobility	Size for terrain scale Shape for required movement, e.g., amoeboid for very rough slither for uphill, cracks spheroid for smooth Gait for roughness
Payload Carrier Transportation	Same as Rover
Antenna Communication	Beacon/Bowl shape Single or arrayed
Shelter provider	Cover over natural enclosure or hut-like in open, single or arrayed
Specialized Task Reconnaissance	Form stable platform for Measuring or collecting operation

ANTS/LARA DESIGN FEATURES

LARA **frame** components are electromechanical structures forming a continuous network of struts which are network of struts which are reversibly deployable/stowable from EMS or MEMS nodes equipped for wireless operation. Payload and subsystem components are attached 'inside' the tetrahedral network, between layers of nodes, and thus protected. After manufacture, the frame could be reduced to a **minimum strut extension size for shipping** to a launch or deployment size.

Nodes and Struts would be used for all functions The greatest number would be structural nodes which deploy/stow flexible struts based on one of several design schemes, ranging from a) telescoping struts extended or contracted by various mechanisms, including cables or springs, and b) double 'tape measure' device which links or unlinks the oppositely wound flexible rolled sheets. Rolls with opposite orientations develop great tensile strength when combined. Similar nodes could be used as attachment points for payloads, such as instruments. These structures are discussed in more detail elsewhere [19,20,21].

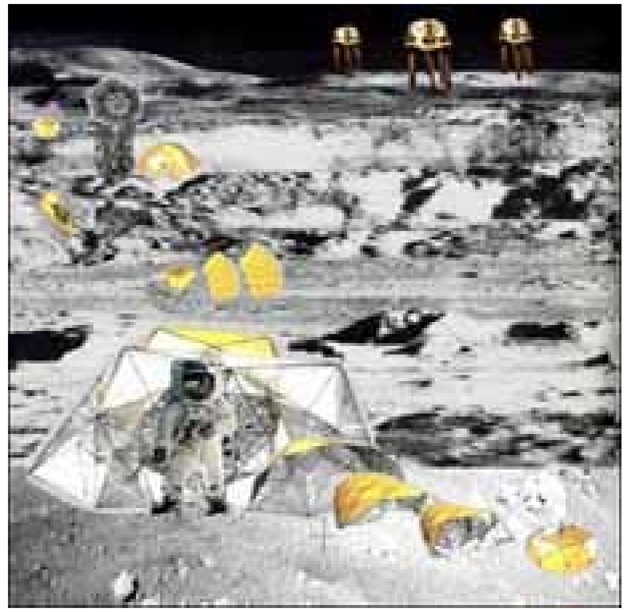

Figure 1. LARA Mission Components, including landers on top, antennae in crater and astronaut shelter in foreground. Amorphous rover in various contortions stretching from back to front of scene.

An **outer covering** for the LARA craft, also discussed in more detail elsewhere [19,20,21], could be provided by specially designed nodes which would deploy carbon fiber composite 'memory' sheets with relatively low aerial density using Polymer/Carbon Nanotube Composite (PNC) springs and structural elements [22,23]. A stack of 'sheet' roll devices could deploy multi-layered sheets for external covering of the desired thickness and reflectivity.

The LARA **Lander** (**Figures 1 and 2)** is formed by flattening the tetrahedral network so that mini chemical propulsion thrusters are effectively attached around the periphery.

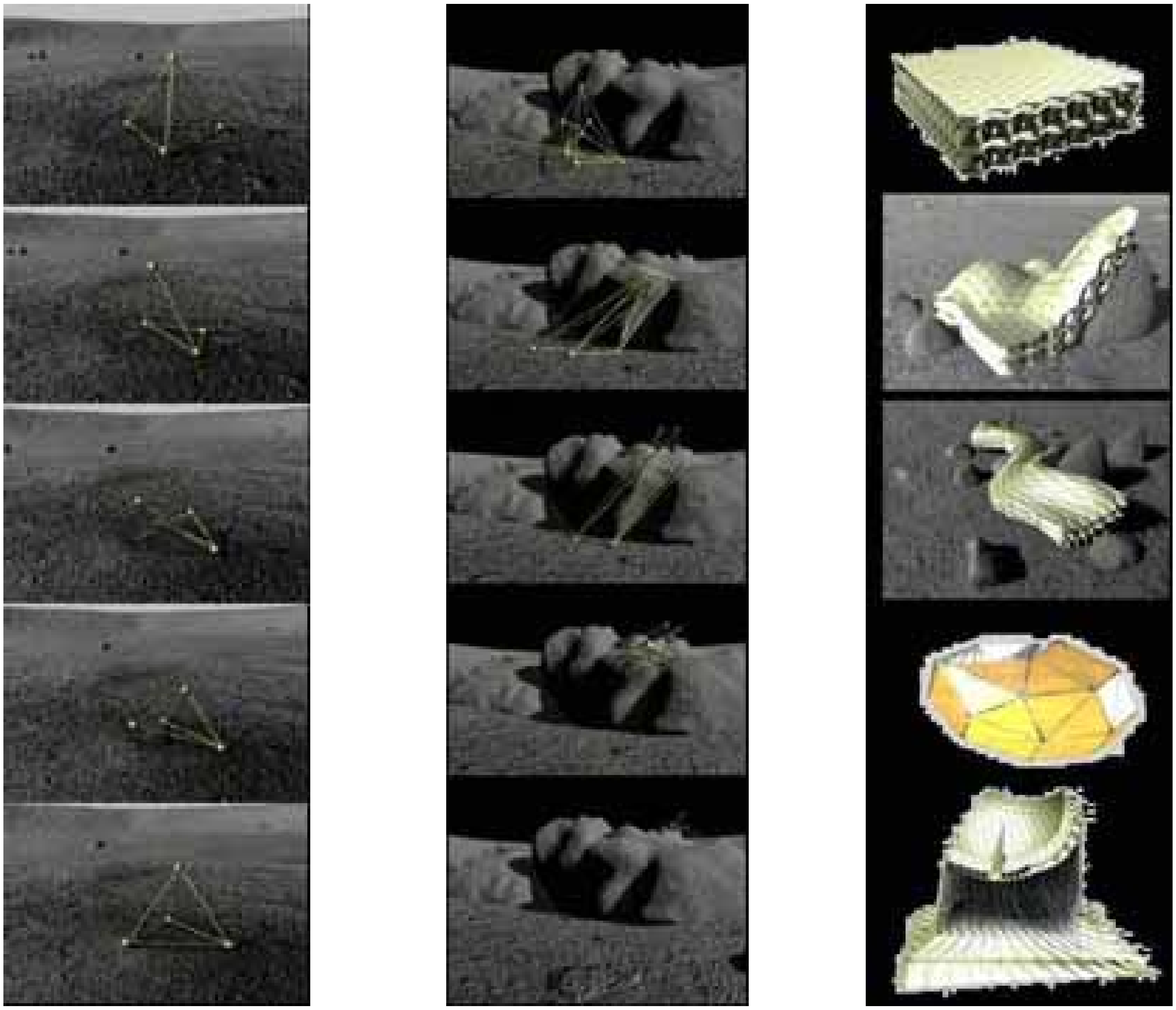

Figure 2: Evolution of Tetrahedral Walker. On left, single tetrahedral walker taking one step. A prototype of this model is currently being constructed. A 4Tetrahedral walker, with an interior node, which could contain payload, is currently being designed and proposed for field testing [19]. In the middle is a 12Tetrahedral Walker illustrating more complex, less punctuated, movements. On right, highly developed movement from multi-tetrahedral amorphous rover which become continuous including, from top, lander becoming amoeboid at landing, transforming to slithering, storing as sphere, and then becoming antenna.

The LARA **Amorphous Rover (**on right in **Figure 2**) is created by continuouscontraction and extension of struts in a way that optimizes the efficiency of movement across a terrain, and thus depends on the variability and scale of the relief and roughness in a given terrain. The ability to control the timing and extent of strut deployment allows control of the scale and gait of the rover.

A single tetrahedron **(Figure 2**), like the prototype we are currently building, rocks from side to side as it moves forward. Put an additional strut at each node and divide that tetrahedron into 4 tetrahedron (like the 4Tet we are proposing to field test), and an inner space is created for attachment of a payload. In a 12Tet model **(Figure 2**), motion is far more continuous [19]. Ultimately, with interconnecting, space filling tetrahedral material, very high degree of freedom movement emerges, more ‘natural’ than wheels, effectively allowing ‘flow’ across a surface and into a particular morphological form.

Examples of morphological forms for the continuous tetrahedral motion can be observed in **Figure 2**. Clear amoeboid-like movement can be observed for very rough surface, more 'natural' than wheels, effectively allowing 'flow' across a surface or into a particular morphological form. For a very smooth surface, or for 'storage' the minimum surface area spheroid, rolling across the ground, could be effective. Uphill climb or slipping through narrow openings could require a slithering snakelike morphology. When surmounting obstacles, the rover could either change its scale, growing in size, or use a climbing motion, pulling itself over using facets on the obstacle itself as 'toe holds'.

LARA craft is transformed into an **Antenna (Figure 2**) whenever significant bandwidth communication is required. The tetrahedral network itself, bowl-shaped above with a broader base below, is equipped to receive and transmit data.

The **Payload** could be placed within active or passive nodes on the 'inside' of the tetrahedral structure. (A continuous network could have an 'inside' and 'outside'.

LARA MISSION SCENARIOS

A wide variety of mission scenarios could be employed in using LARA systems. Deployment and use could be either entirely robotic and autonomous, or through a human interface. The human interface could be remote in near real time, through telepresence, or in situ, acting as extensions for a human crew active on the surface.

LARA craft could first land payloads autonomously, then form roving 'advance reconnaissance teams', mapping, gathering and analyzing samples and images of the terrain for use in site selection. Such analysis of samples, to determine elemental, mineral, water, biogenic material, or rock abundances, or terrains, to determine stratigraphy, morphology, age, would inevitable lead to the identification of sites with important clues on the origin of planets, the solar system, or life itself. Whenever necessary, rovers could form antenna to transmit findings and receive instructions. Such systems could also be used to provide shelter, by creating, seeking, and enclosing natural semi-enclosed formations. LARA craft could also find, collect, or mine materials of use in exploration or construction. A network of LARA craft could be used to form a temporary or permanent communication, navigation, or observatory facilities.

Table 7: LARA Requirements

Launch Date: 2010-1015
Duration: Months or even years
Location: 1.0-2.0 AU
Spacecraft Mass: 10-50 kg
Spacecraft Materials: 10-100 g/cm^2
Power system: Solar Cells or Nuclear Batteries
Power system mass: 5 kg
Power requirement: 10-30 Watts
Torque at node:
Space Propulsion system: Chemical Mini-thruster
Ground Propulsion system: Node and Strut
Operations:
- Autonomous or through link with crew
- Individual or collective operation
- Cover tens of kilometers per day
- No single point failure
- Robust to minor faults and major failure

REALIZING THE ANTS CONCEPT: REQUIREMENTS AND ENABLING TECHNOLOGIES

As part of the ANTS/LARA study, we are determining the major requirements for such mission **(Table 7**). We should be able to meet all of these requirements with anticipated, incremental technology developments over the next two decades. Anticipated incremental improvements in MEMS technology subsystems will be useful, but are not essential. Improvements in the efficiency of nuclear batteries and solar cells, communication and tracking devices, would also be useful in reducing weight and power requirements.

The development of **autonomous navigation without appendages** is an area we are now actively engaged in developing. We have already developed simulations of the movement of single, 4, 12, and continuous tetrahedral structures (See still and movies at the official ANTS website [1]). The first demonstration model of an EMS-level (ART) single ANTS tetrahedron, designed to be a walker (TET), will be completed in October 2004 (TRL 3). Plans are underway to test the TET in January 2005 in Antarctica with remote operation via the Internet using a 3-D graphical user interface. We have completed a preliminary conceptual design of a 4-tetrahedron system (4-TET) capable of carrying a scientific payload in a central node, and have proposed to build and test that system on a field campaign in Iceland ('Mars on Earth') (TRL 6). The next milestone will be to build the 12TET model. At this level, the ability for 'continuous' movement clearly emerges.

LARA utilizes a totally new type of space architecture based on an autonomous, addressable, reconfigurable components. The potential flexibility and adaptability of such a system demands a level of **artificial intelligence** we are in the process of developing through our role in ST-8 COTS High Performance Computing and Multi-agent Simulations using Beowulf clusters here at GSFC [1,9c].

Another key technology driver is the availability of **carbon-based materials** to form surface structures in order to minimize deployment, mass, and power requirements. Ultimately, to minimize the mass and power requirements, ANTS structures will be built entirely on carbon-based materials. Currently available carbon fiber composites [23] are the most lightweight, durable, and rigid materials that are currently available. Specially manufactured thin sheets of this carbon film on fiber material with shape memory have already been manufactured [22]. A particular area of concern for our application would be the ability to 'retain' memory over potentially millions of deployments, and the power expenditure requirement to hold the material at partial deployment.

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